Luminous Efficiency of Hypervelocity Meteoroid Impacts on the Moon Derived from the 2015 Geminid Meteor Shower

D. E. Moser[1], R. M. Suggs[2], and S. R. Ehlert[3]
[1]Jacobs, ESSSA Group, Meteoroid Environment Office, Marshall Space Flight Center, Huntsville, AL 35812 USA
[2]NASA, EV44, Meteoroid Environment Office, Marshall Space Flight Center, Huntsville, AL 35812 USA
[3]Qualis, ESSSA Group, Meteoroid Environment Office, Marshall Space Flight Center, Huntsville, AL 35812 USA

Abstract

Since early 2006 the Meteoroid Environment Office (MEO) at NASA's Marshall Space Flight Center has routinely monitored the Moon for impact flashes produced by meteoroids striking the lunar surface. Activity from from the Geminid meteor shower (GEM) was observed in 2015, resulting in the detection of 45 lunar impact flashes (roughly 10% of the NASA dataset), in about 10 hours of observation with peak R magnitudes ranging from 6.5 to 11. A subset of 30 of these flashes, observed 14-15 December, was analyzed in order to determine the luminous efficiency, the ratio of emitted luminous energy to the meteoroid's kinetic energy, using the technique of [1]. The resulting luminous efficiency, found to range between $\eta = 1.8 \times 10^{-4}$ and 3.3×10^{-3}, depending on the assumed mass index and flux, was then applied to calculate the masses of Geminid meteoroids striking the Moon in 2015.

Background

Meteoroids striking the Moon create an impact flash observable by Earth-based telescopes. Their kinetic energy (E_k) is converted to luminous energy (E_l) with some unknown luminous efficiency (η), which is likely a function of meteoroid velocity (among other factors).

$$E_l = \eta\, E_k$$

The luminous efficiency is imperative to calculating the kinetic energy and mass of a meteoroid, as well as meteoroid fluxes, and it cannot be determined in the laboratory at meteoroids speeds and sizes due to mechanical constraints.

Observations of impact flashes associated with meteor showers can be utilized to calculate η by making use of Earth-based measurements of shower flux, $F(m_o,t)$ to a limiting mass m_o, and mass distribution index, s. Luminous efficiency is estimated from a comparison of the total number of events detected on the Moon to the total number expected in the monitored area (A) based on shower observations on Earth in time, t:

$$N(E_l) = \left(\frac{2\,E_l}{\eta\, m_o V^2}\right)^{1-s} \int_{t_1}^{t_2} F(m_o,t)\, A(t)\, dt$$

Theory

The technique for determining luminous efficiency incorporates the method of [1], restated here. The number of meteoroids that impact the Moon in time span t_1 to t_2 is

$$N = \int_{t_1}^{t_2} F(t)\, A(t)\, dt \qquad (1)$$

where F(t) is the flux as a function of time and A is the observed lunar area that is perpendicular to the meteor shower radiant also as a function of time.

The cumulative flux distribution of meteoroids of mass m is given by

$$F(m) = F(m_o)\left(\frac{m}{m_o}\right)^{1-s} \qquad (2)$$

where F(m) is the flux of particles having mass greater than m, $F(m_o)$ is the flux of particles of known mass greater than mass m_o, and s is the mass index.

The masses of the meteoroids impacting the Moon are unknown. For an impactor of mass m and velocity V, the kinetic energy is $E_k = \frac{1}{2} m V^2$. Substituting this into Eq (2) gives a cumulative flux distribution as a function of kinetic energy.

$$F(E_k) = F(m_o)\left(\frac{2\,E_k}{m_o V^2}\right)^{1-s} \qquad (3)$$

Solving $E_l = \eta\, E_k$ for E_k and substituting this into Eq (3) gives a cumulative flux distribution as a function of luminous energy.

$$F(E_l) = F(m_o)\left(\frac{2\,E_l}{\eta\, m_o V^2}\right)^{1-s} \qquad (4)$$

Using Eq (4), Eq (1) becomes the number of lunar meteoroid impacts producing luminous energies greater than E_l in the time span t_1 to t_2

$$N(E_l) = \left(\frac{2\,E_l}{\eta\, m_o V^2}\right)^{1-s} \int_{t_1}^{t_2} F(m_o,t)\, A(t)\, dt \qquad (5)$$

This result is comparable to Eq (4) of [1] and identical to the treatment in [5].

Instruments

The NASA MEO has routinely monitored the Moon for impact flashes produced by meteoroids striking the lunar surface in order to determine the flux in the 10's g to kg size range [2].

Facilities
- Automated Lunar and Meteor Observatory (ALaMO) in Huntsville, Alabama USA (34.7°N, 86.7°W)
- Lunar impact monitoring program since 2006

Instruments
- Simultaneous observations using 2 identical Celestron 0.35m telescopes
- Watec 902-H2 Ultimate monochrome CCD video cameras
- Interleaved 30 fps video digitized and recorded straight to hard drive

FOV
- Earthshine portion of the Moon only
- Horizontal FOV ~20' (Fig 1)
- 4×10^6 km² area on the leading or trailing edge of surface

Analysis
- LunarScan software [3] detects impact flashes in the video
- Photometric analysis following [2, 4]

Scheduling
- Observations when illumination ~10-50%
- Max. of 10 observing nights/month during routine obs.
- 10.15 hr during the 2015 Geminid meteor shower (see Table 1)

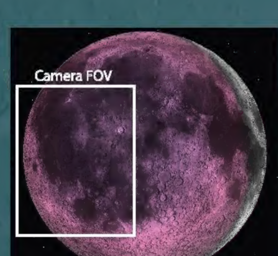


Fig 1: GEM visibility (pink) 14-15 Dec 2015

Table 1: Lunar observations during the Geminids; only 14-15 Dec was used for this study

Date	Timespan (UT)	Tot. Time (hr)	# Impacts	Raw rate (#/hr)
14-15 Dec 2015	23:25-01:41	2.26	32	14.1
15-16 Dec 2015	23:21-02:41	3.33	9	2.7
17-18 Dec 2015	23:44-04:18	4.56	4	0.9

Observations

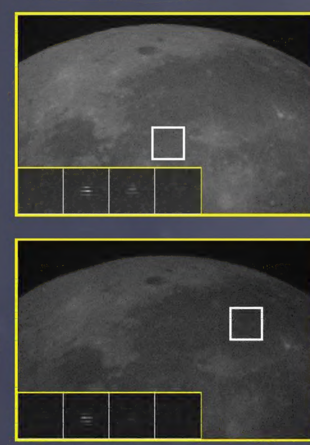


Fig 2: GEM lunar impact flashes observed on 15 Dec 2015 at (top) 00:07:21 UT and (bottom) 01:20:43 UT, with flash frame sequence inset.

Impact flashes, Fig 2, were associated with the Geminid meteor shower [2] and flash locations, Fig 3, were consistent with Geminid geometry. Photometric analysis utilizing [2, 4] yielded magnitudes and luminous energies.


Fig 3: Impact flash locations

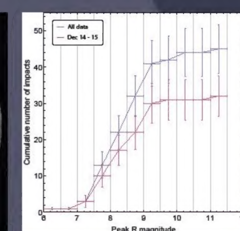
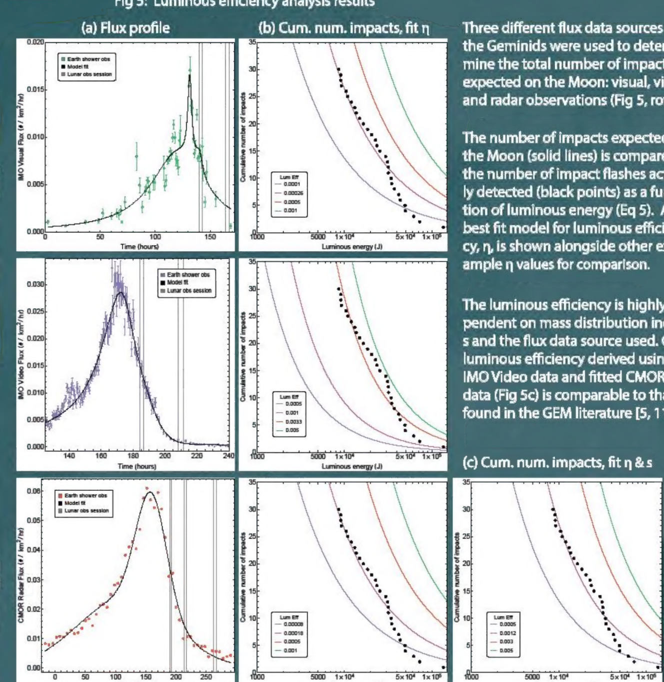


Fig 4: Cum. histogram of flash mag

The cumulative histogram of flash magnitudes, Fig 4, shows that a turnover occurs at $m_R = 9.5$ for the whole dataset as well as December 14-15. This feature indicates a completeness limit of $E_l = 8.3 \times 10^3$ J. Observations recorded 15-16 December and 17-18 December were excluded from this study as a completness limit could not be determined. These selection criteria reduced the dataset from 45 to 30 impact flashes.

Results

Fig 5: Luminous efficiency analysis results



Three different flux data sources for the Geminids were used to determine the total number of impacts expected on the Moon: visual, video, and radar observations (Fig 5, rows).

The number of impacts expected on the Moon (solid lines) is compared to the number of impact flashes actually detected (black points) as a function of luminous energy (Eq 5). A best fit model for luminous efficiency, η, is shown alongside other example η values for comparison.

The luminous efficiency is highly dependent on mass distribution index s and the flux data source used. Only luminous efficiency derived using IMO Video data and fitted CMOR data (Fig 5c) is comparable to that found in the GEM literature [5, 11].

Table 3: Best fit Geminid luminous efficiency results by data source

$F(m_o,t)$	m_o (kg)	s	η	m (g)	Mass range (g)
IMO Visual	1.0×10^{-6}	1.69	2.6×10^{-4}	55	60 – 900
IMO Video	1.0×10^{-6}	1.95	3.3×10^{-3}	4	4 – 70
CMOR radar	1.8×10^{-7}	1.69*	1.8×10^{-4}	79	80 – 1000
Fitted CMOR radar†	1.8×10^{-7}	1.80	1.2×10^{-3}	11	10 – 200

Calculations utilize Eq (5) with constant perp. $A = 3.0 \times 10^6$ km², v = 35.1 km/s, and t as in Table 1.
*s=1.69 from [10]. †Results from fitting the cum. number of impacts to CMOR data in both η & s.

Summary

The NASA MEO recorded 30 impacts brighter than $m_R = 9.5$ during the night of the Geminid peak, 14-15 December 2015. Utilizing the technique of [1], the luminous efficiency of Geminid meteoroids was calculated to be between $\eta = 1.8 \times 10^{-4}$ and 3.3×10^{-3}, depending on the flux data source and mass distribution index assumed. This range of luminous efficiency values implies impactor masses of roughly 4–1000 g. Luminous efficiency values from IMO Video and fitted CMOR radar were in good agreement with that found by [5, 11], though previous studies utilized less impact data (by a factor of more than two). Values of η determined from IMO Visual and CMOR radar were an order of magnitude smaller and require more investigation. **It must be noted that this technique for determining luminous efficiency is highly dependent on mass index.**

References

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